Numerical simulation of deposited behaviours of Al particle on Mg substrate in supersonic particles deposition

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Abstract

ANSYS/LS-DYNA is used to simulate supersonic particles deposition process of Al particle impinging on Mg substrate. Critical velocities of particle at different spraying temperatures and deformation, highest temperatures, stress and strain of particle/substrate are studied. The results show that with the increasing of spraying temperatures, the critical velocities experience a small amplitude decrease. For the two aspects of single particle and two-particle impingements, the highest temperature rises with the increasing of initial temperature and the deformation morphology and stress and strain of particle/substrate vary with/without tamping effect. Upon the effect of tamping, the flatten ratio of pre-deposit particle is bigger than the particle without the tamping effect at the same velocity. The values of maximum stress and strain of two-particle with tamping effect are both higher than single particle impinging. The change gradient of stress without tamping effect is much steeper in comparison of two-particle impinging with the velocity increasing while the change curve tendency of maximum strain is similar to the flatten ratio.

Keywords: supersonic particles deposition, simulation, tamping effect, critical velocities, stress and strain

1 Introduction

Supersonic particles deposition (hereafter referred to as SPD) is based on the cold spray technique and develops rapidly as a new spraying process [1-3]. Cold spray was initially developed in the mid-1980s at the Institute for Theoretical and Applied mechanics of the Siberian Division of the Russian Academy of Science in Novosibirsk [4-6]. The compressed gases, generally nitrogen, helium and air, or their mixtures, are used in cold spray process. The feedstock powders are injected into a de-Laval type nozzle by the gases and accelerated to a supersonic velocity, these particles impinge on the substrate and form the coating [7-9]. In the impinging process, the impact behaviours can bring high plastic deformation, contact stress and plastic strain. A continued flux of impinging particles may result in a continuously impinging through high velocity impacts between particles arriving at the substrate and those already deposited. The occurrence of bonding on particle impact is widely regarded to be related to the occurrence of shear instabilities at the inter-particle boundaries, due to high strain rate deformation [10].

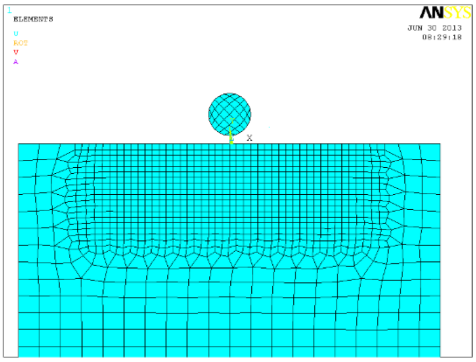
The impinging process between the feedstock powders and the substrate finishes in a very short time period, usually less than 0.1ms. With a transient process, the colliding and deformation of the particle/substrate cannot be observed by experiments easily in the SPD process [11, 12]. M. Grujicic [13] proposed that jet-like metals might produce interfacial roll-ups and vortices under the Kelvin-Helmholtz effect in this rapidly process, which results in a mechanically combine on a substrate of particles. B. Gyuyeol [14] studied the deformation and the critical velocities of single particle impinging on substrate with different hardness of materials using computational methods. ZHOU [15] studied the deposition behaviour of multi-particle impact of Cu coating, tamping effect of continuous particles was proposed.

The light metals (such as Al, Mg) are so active that they are inappropriate to prepare by high temperature spraying processing, and SPD technique provides an effective method to tackle the defects of melt, oxidation and the phase transition of materials, which exists mostly in traditional thermal spraying. In this article, the deformation behaviours and tamping effects of Al particles and Mg substrate are investigated by computational methods. Meanwhile, the flatten ratio, maximum stress and strain of single particle and two-particle impinging behaviours are studied.

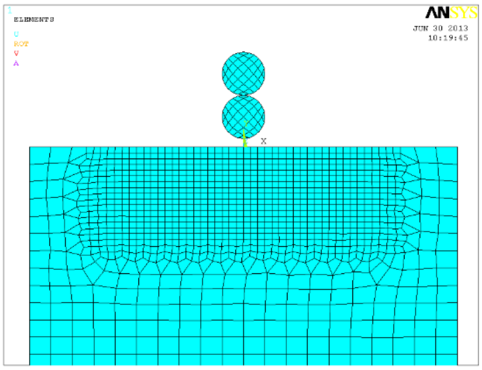
2 Numerical modeling

2.1 FINITE-ELEMENT METHODOLOGY

The impinging behaviours of particles on the substrate in SPD are analyzed using the finite-element program ANSYS/LS-DYNA. The particle is assumed to impact the substrate vertically, a schematic of computational domain vertical collision of spherical particle and cylindrical substrate is given in Figure 1. The finite element model and grid meshes of single particle impinging on substrate are shown in Figure 1(a), which is referred to without tamping effect; and the two-particle impinging in Figure 1(b) can be seen as with tamping effect, correspondingly. The size of particle is 50μm average and the cylindrical substrate is adequate for particles and substrate deformation, the impacting domain is two twice than the particle size [16]. Four-node bilinear shell elements, hourglass control and two-dimensional automatic single surface contact are used in the simulation process.



a) single particle without tamping effect



b) two-particle with tamping effect.

FIGURE 1 2-D finite element models and grid meshes of impinging

a. Boundary conditions.

The boundary condition of underside of substrate is wall-boundary, and the other faces are deemed as freedom boundaries. In these models, the interaction of particle/substrate is assumed to be an adiabatic process, the shear friction of particles on substrate is viewed as a negligible quantity. The initial temperature and pressure of spraying process are set to 300K and 0.65MPa respectively.

b. Material models.

Both particles and substrate are set as strain-hardening, strain-rate sensitive and thermal-softening materials, and the materials are assumed to comply with Johnson-Cook plasticity model [17], the equivalent normal plastic deformation resistance σ is written as in Equation (1).

$$\sigma = [A + B\varepsilon_p^n][1 + C\ln(\varepsilon^*)][1-(T^*)^m], \quad (1)$$

where $\varepsilon_p{}^n$ is the equivalent normal plastic strain, ε^* the equivalent plastic strain rate normalized with respect to a reference strain rate, constants *A*, *B*, *n*, *m* and *C* are determined by material properties, and T^* the temperature which can be denoted by initial and the melting temperature, respectively[17-18]. The materials may lose effectiveness at the colliding process, so we adopt the losing-effectiveness modeling of material based on Johnson-Cook plasticity model, the accumulation damage law is as follows in Equation (2).

$$D = \sum(\Delta\varepsilon / \varepsilon_f) \quad (2)$$

where $\Delta\varepsilon$ is the increasing of effective plastic strain, ε_f the losing effectiveness strain, it is a function of effective strain, plastic strain rate and temperature [17, 18]. Then some material properties of Al and Mg alloy are shown in Table 1.

TABLE 1 Some material properties of feedstock and substrate

	Materials	Young's modulus (GPa)	Density (g/cm³)	Poisson's ratio	Specific heat capacity (J/kg·K)	T^*(K)
Feedstock	Al	68.9	2.7	0.33	904	1189
Substrate	Mg	44.8	1.8	0.35	10.4	986

3 Results and discussion

3.1 CRITICAL VELOCITY OF PARTICLE

The particle velocity is one of the dominant factors in the process of coating forming. It has been shown that the sign of an adequate degree erosion deforming on the substrate surface of spraying particle is adiabatic shear instabilities formation, which means that the critical velocity is as a particular minimum particle velocity to form a coating on the substrate surface [13, 19-20]. In the simulation process, Al particles with different spraying temperatures exist different critical velocities, the spraying temperatures play a more significant role in promoting velocities than other parameters.

The input of temperature parameters is by a little program which is inserted into the ANSYS main programs and the algorithm of the temperature program is based on the principle of Thermo-Solid Coupling, while the other parameters such as spraying pressure, particle size, distance to exit of nozzle, the radial position are set as constants in this paper. The critical velocities at different spraying temperatures are shown in Table 2. The results show that the critical condition of successful deposit of particles onto substrate is of dependence on implementation by increasing spraying temperatures.

TABLE 2 Critical velocity of Al-alloy powder at process pressure 0.65MPa

Spraying temperature (K)	Critical velocity (m/s)
300	720
400	714
500	678
600	653
700	631
800	616
900	588

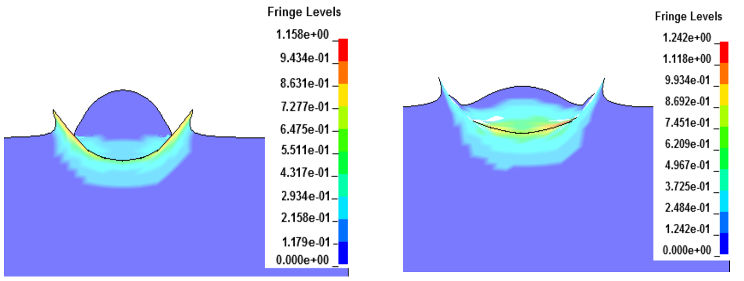
3.2 DEFORMATION BEHAVIOURS OF PARTICLE AND SUBSTRATE

Figure 2 shows the simulated deformation morphologies and value of strain of single particle and two-particles on substrate at different moments at the critical velocity of

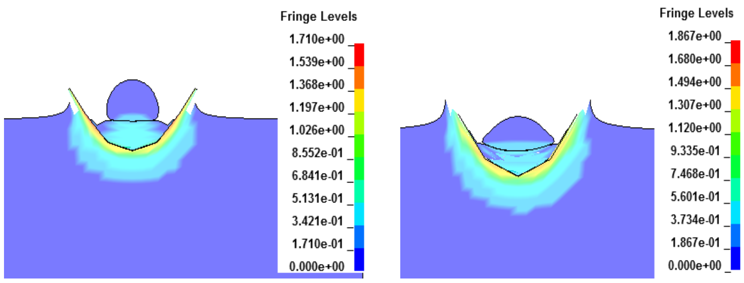
720m/s (temperature=300K, pressure=0.65MPa).

It is obvious that the deformation is severe and the strain is intense, the particles become flat and craters take place on the substrate (Figure 2). With the contact time increasing, a jet-type flow of the materials at the interface generates on both impinging aspects. The jets flow occurs only in the substrate at 20ns, the metallic jets are discovered on the interface of particle and substrate at 40ns. In Figure 2c, 2d we can detect that the pre-deposited particle is flatter than single particle impinging (Figure 2a, 2b)) at the same moment, and the deformation of subsequent particle is also intense because they are same materials and deform easily of consubstantial solid material.

The maximum strain takes place at the interface of particle and substrate, and locates at the side of substrate, we can infer that at these places the deformation is severe and the temperature may be sufficient to melting point of the materials. The specific heat capacity of Mg is much lower than Al (Table 1), the capacity of heat dissipation of Mg is weaker and the temperature can be raised to its melting point more easily than Al, so the maximum of strain is on Mg substrate [8]. And the continuous particles improves the kinetic energy of pre-deposited particle, which results in promotion of converting to internal energy, so the value of strain of the interface with tamping effect are higher than the interface without tamping effect in Figure 2.



a) single particle at 20ns b) single particle at 40ns



c) two-particles at 20ns d) two-particles at 40ns 40ns

FIGURE 2 Deformation morphology and value of strain of particles at 750m/s

The initial temperatures generate a profound influence on the deformation of solid particles as well. The highest temperature of the impinging process is located on tangent edge of the Mg substrate and the maximum value of temperature increases with the growing of the initial value, the results of the influence of initial temperature on the highest temperature are shown in Figure 3. From the curves, we can infer that the highest temperatures of single particle impinging process at different initial temperatures are all a little smaller compared with the two-particle impinging process. The highest temperature reaches to nearly 900K which is proximity to the melting point of Mg substrate when the input data of initial temperature is 700K, that is to say, the substrate will probably melt if there is a continuing increase of the initial temperature. This situation should be avoided in our experiments because the coating in SPD melts barely in the spraying process. So the preheat temperatures in our experiments are practically lower than 400K so that we can achieve the champion coatings.

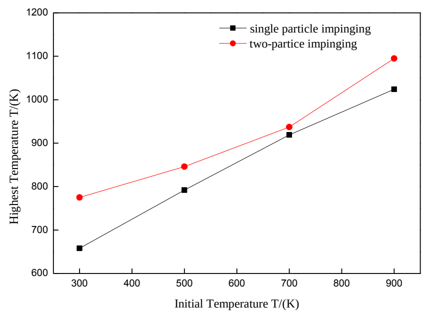


FIGURE 3 Influence of initial temperatures on highest temperatures in impinging process

Flattening ratio which is defined as the ratio of the diameter of deformed particle to that of a spherical particle of the same volume, is often used to estimate the deformation of impinging particles. In the impinging process, the subsequent particle breeds a tamping action on the pre-deposited particle [21], which results in different aspects of deformation, the ratios of single particle (without tamping effect) and multi-particle (with tamping effect) on the Mg substrate at different velocities are shown in Figure 4.

As can be seen from the linear fit of the measured data in Figure 4, the flattening ratios do not increase remarkably with the critical particle velocities, however, the flattening ratios of particles with tamping effect increase partly at the same critical velocity comparing with single particles. Therefore, the tamping action on pre-deposited particle by subsequent particle plays a vital role in particle deformation and shaping of coatings.

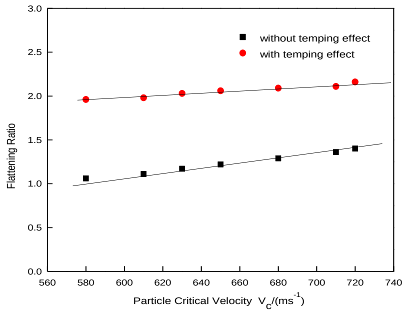


FIGURE 4 Influence of tamping effect on the particle flatten ratios

3.3 STRESS AND STRAIN DISTRIBUTION

The relationships between maximum stress, strain and impinging moment of pre-deposited particle are shown in Figure 5. It can be easily obtained that strain and stress of pre-deposited particle are both mutant at about 10ns, the strain remains constant in contrast with the occurrence of stress fluctuation as shown in Figure 5. The maximum value of strain is at the interaction edge and the strain curve states that the thermal-softening effect is superior to strain-rate hardening characteristics of Mg substrate, which results in the plastic flow and the adiabatic shear instability at 5~10ns. Meanwhile, the maximum strain remains 1.325 with increasing of contact time. Similarly, the stress curve states the plastic deformation increases rapidly in initial colliding process. The flow stress fluctuations are investigated at 20-35ns and 40-50ns. At 20-35ns, high-rate visco-plastic deformation occurs at the interface and interior of materials where the adiabatic shear instability takes place. At this occasion, the metallic jets release the stress while the visco-plastic deformation stores stress at the same time, so the stress presents fluctuations at this stage. At 40-50ns, the kinetic energy of particles transfers to internal energy of substrate and particles and the instantaneous stress of particles which produced by impinging also transmits to substrate. The stress in substrate dissipates most then the stress reduces to 1000MPa rapidly. Besides dissipation, the stress grows as the contact time increases so the fluctuation is founded at this time interval.

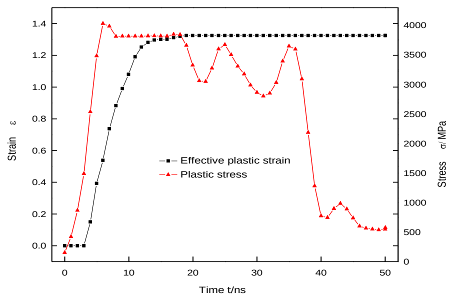


FIGURE 5 Simulated temporal developments of stress and strain of particle with tamping effect

The influences of particle critical velocities with/without tamping effect on maximum stress, strain are shown in Figure 6. As we can see that the maximum stress of particle increases with the soaring of critical velocities whether the tamping effect exists (Figure 6a), but the maximum stress with tamping effect is higher than that without tamping effect obviously. With the tamping effect, the maximum value is approximately 3 times than the particle deposit without tamping effect at the velocity of 580m/s, so we can presume the maximum value of pre-deposited particle is located at the interface of pre-deposited particle and the follow-up particle. At the velocity of 720m/s, the deformation of particle is adequate and similar, so the maximum stress value increases slowly. The changes of strain of particles with different deposit aspects are similar to the flattening ratio (Figure 6b), since the changes of strain are synchronous with the deformation of particle with the increasing of time, the degree of craters of substrate and flattening ratio of particle is associated with the tendency of the effective plastic strain of particle.

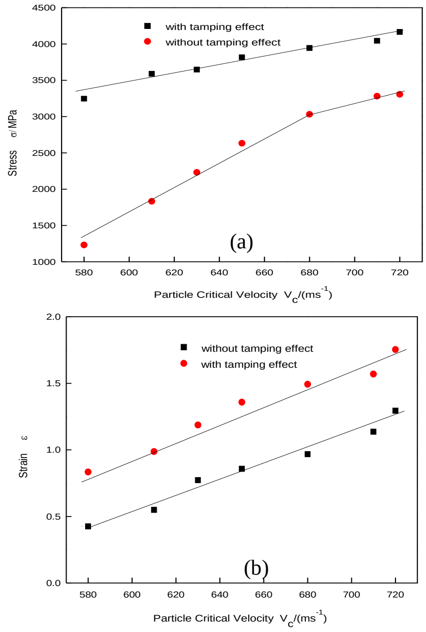


FIGURE 6 Stress and strain distribution at different critical velocity: (a) stress distribution (b) strain distribution

4 Conclusions

1) The critical velocity of particle decreases with the rising of spraying temperature, so in the actual spraying process, the extra cost of increment gas pressure to increase particle velocity can be cut down by increasing the spraying temperature, and the spraying efficiency is souped-up.
2) Under the tamping effect, the flatten ratio of particle and the crater depth of substrate are greater than the particle/substrate without tamping effect, which states that the deformation of two-particle is more severe and the interlock of the interface is closeness.
3) The preheat temperature in experiments should be lower than 400K to avoid the excessive high temperature which will probably results in the melting of substrate material. The maximum stress of particle/substrate is concussion with an increase of impinging time while the strain tends to a

stable maximum value at 720m/s of two-particle impinging onto substrate. With the critical velocity increasing, both of the stress and strain increase partly, and the maximum value of stress and strain are higher with tamping effect compared with the single particle impacting without tamping effect.

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